MAGELLANIC CLOUD OBJECTS

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Abstract: In this review, the considerable contributions of IUE to understanding the composition, stellar evolution, interstellar medium, and extinction of the Clouds are discussed and compared with those for the galaxy. Future directions for UV work are suggested.

INTRODUCTION

One of the early surprises of IUE was the discovery that hot stars in the Magellanic Clouds were accessible. There are now some 1000 IUE images of Cloud objects and over 100 papers in print on these data. The research falls into a few main subject areas by numbers of papers, with the principal ones being the hot stars themselves, interstellar extinction studies, cloud halo and ISM, and X-ray sources. These will all be described, but I would like to try to link the different topics with what is probably the single most significant difference between the Clouds and the galaxy — the heavy element abundances - so that is where we will begin. I will also attempt to point to where future work will be needed in each area.

ELEMENT ABUNDANCES

The element abundances in the Magellanic Clouds are of interest to many aspects of research. Most fundamentally, the abundances are a record of the stellar history of a galaxy, and comparison between our own and other galaxies is of great significance. It has also become clear that these abundances affect many ongoing processes in a profound way - principally by affecting the opacity and scattering of radiation. Observed differences between the Clouds and our galaxy in the behaviour of stellar envelopes, stellar mass-loss, interstellar extinction, the determination of absolute fluxes, and strong X-ray source fluxes, are all known examples of where this is important, and they will be dealt with in this review. Other as yet unexplored areas where the effects may be important are novae and their light curves, stellar spectral classification, and stellar evolution in general, including supernovae and compact stellar remnants. To start with, we look at the contribution of IUE to abundance determinations in the Clouds.

It has been noted by many workers over the years that the absorption lines of Cloud stars are weak compared with their galactic counterparts, and generally accepted that this indicates real abundance differences. The UV spectral region contains particularly valuable C lines that the visible region lacks, for this work, as well as many lines vital to the determination of

ionisation fractions in combination with visible region lines. The determination of C abundances has been done by Dufour, Shields and Talbot (1982), and reviewed by Dufour (1984), from H II regions. Their important result is that in the SMC C is depleted (with respect to the galaxy) more than N or O, while in the LMC, N is depleted more than C or O. They argue that N and O are initially generated by massive (>10M_0) star evolution, and C from less massive (4 to 10 M_0) stars. Thus C/N and C/O starts low and rises with time as the less massive stars begin to evolve. Later still, when <4 M_0 stars have evolved, C/N will decrease again, since these stars produce N.

	$12+\log N(X)/N(H)$						
ELEMENT	SMC[a]	LMC[a]	Orion[a]	Sun[b]	PN[c]	SMC-Sun	LMC-Sun
C	7.16	7.90	8.46	8.65	8.93	−1.49	−0.75
N	6.60	6.94	7.48	7.96	8.68	−1.36	−1.02
O	8.05	8.38	8.60	8.87	8.77	−0.82	−0.49
Ne	7.34	7.68	7.79	8.05	8.14	−0.71	−0.37
S	6.61	7.01	7.12	7.23	7.34	−0.38	−0.22
Ar	5.77	6.10	6.27	6.57	6.50	−0.80	−0.47
C/O	−0.89	−0.48	−0.14	−0.22	0.16	−0.67	−0.26
C/N	0.56	0.96	0.98	0.69	0.25	−0.13	+0.27
N/O	−1.45	−1.44	−1.12	−0.91	−0.09	−0.54	−0.53

Table 1. Relative abundances in MCs and galaxy from Dufour et al. (1982).

The situation is summarised in Table 1, and this scenario sets out reasonably clearly the evolutionary history of the Clouds compared with the galaxy. Maran et al. (1982) used the IUE to study planetary nebulae in the Clouds, and obtained interestingly different results. They find C abundances only slightly less than the galaxy, while other elements are depleted by the "normal" amounts. Their finding in other words is that in PN ejecta, C is 40 times the local ISM value in the SMC and 6 times in the LMC. They thus find that at present planetary nebulae are the principal source of C enrichment in the Clouds, and that the C generation processes in Cloud stars are roughly the same as in the galaxy - an important datum for stellar evolution theory. Stecher et al. (1982) discuss the central stars of PN in the Clouds and using IUE fluxes derived (Eddington limiting) masses from the deduced bolometric fluxes. These turn out to be ~ 1 M_0, higher than the 0.6 M_0 generally accepted for galactic PN. They discuss some interesting possible explanations of this. (A further factor, for which there is now some other evidence), is that the Clouds may be closer than the present canonical values.)

These kinds of studies are unique to the far UV and are performed with difficulty with IUE, due to its low sensitivity, low dynamic range and limited photometric accuracy. However, the importance of the results will make the ST spectrographs and other high signal-to-noise instruments very desirable for future work.

INTERSTELLAR EXTINCTION

One of the most spectacular results from IUE has been the study of the UV extinction laws in the Clouds. By means of comparison of reddened and unreddened stars of the same spectral type and from model fitting to stars of known spectral type, it has been found that the UV extinction is different in the two Clouds, and in the galaxy (Koornneef 1982, Morgan and Nandy 1982, Hutchings 1982, Lequeux et al. 1982). The mean extinction characteristics are shown in fig. 1, although there are exceptions in all three galaxies which bridge these differences. The shape of the SMC mean extinction curve is still the subject of some debate and research, but the basic characteristics seem well established. Once again, there is a clear progression from SMC to LMC to galaxy. These results are profound because they show us that the relation between perceived and intrinsic flux in any galaxy cannot be taken for granted, and also that the properties of the interstellar medium are strongly variable between galaxies.

Another aspect of this study has been the determination of gas to dust ratio from the measurement of Lyman α absorption simultaneously with extinction. This shows (Koornneef 1984, Lequeux et al. 1984) that the ratio N_H/E_{B-V} is 17 times the galactic value in the SMC and 4 times in the LMC (fig. 2), thus showing the same sequence evident in the extinction itself. These factors are like the C abundance ratios, rather than Si, O suggesting a connection with graphite. The numbers are probably more reliable than determinations by other methods and instruments. A problem is the separation of foreground Ly α, needing higher resolution.

It has been suggested that the grain sizes are smaller in less evolved galaxies, to account for the far UV differences. More recently, however, Nandy (1984) and Bromage and Nandy (1983) have indicated that the principal difference may be the amount of graphite in the ISM (fig. 3), which links us back once more with the C abundance evolution. Lequeux et al. (1984) reached similar conclusions about the role of graphite. In studies of objects in M33, a galaxy similar in mass and evolution to the LMC, it has been found that an extinction law like the LMC is more appropriate than a galactic one (e.g. Massey and Hutchings 1983). Clearly, future work will need to investigate these differences more deeply, in as many local group galaxies as possible. The present indication is that the extinction curve is strongly linked with the evolutionary state of the galaxy, but it needs quantification and a proper understanding of the local purturbations in each galaxy.

HOT STARS AND STELLAR WINDS

As is well known, the principal OB star stellar wind lines are the UV resonance lines of N V, Si IV, and C IV, and IUE studies of these in galactic stars have been numerous and fruitful (e.g. Hutchings and Von Rudloff 1980; Garmany and Conti 1984). The study of MC supergiants has added significance since the differential distance and reddening effects which plague galactic studies, are largely eliminated. Studies of Cloud stars have revealed a number of differences in the stellar winds compared with the galaxy (Hutchings

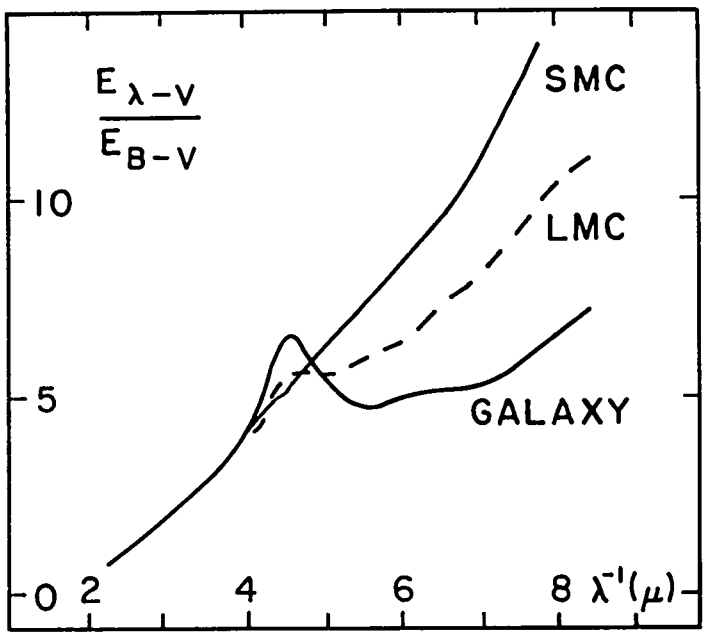

Fig. 1. Mean UV extinction laws, from Lequeux et al. (1984).

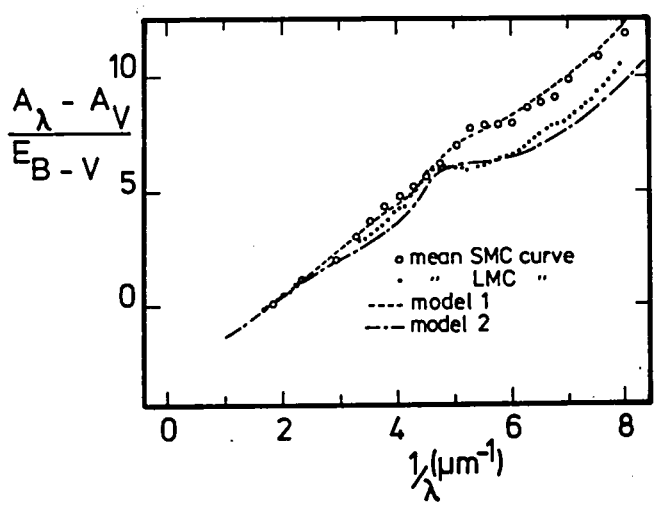

Fig. 2. Model fitting to mean extinction curves (Nandy 1984). Model 1: zero graphite; model 2: 35% galactic graphite.

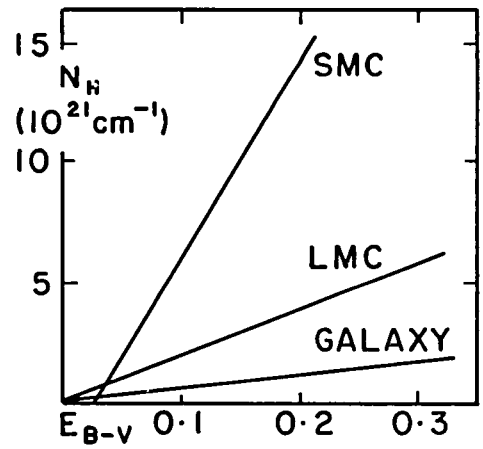

Fig. 3. Mean gas to dust ratio lines, from Lequeux et al. (1984). Diagram covers range of measured values.

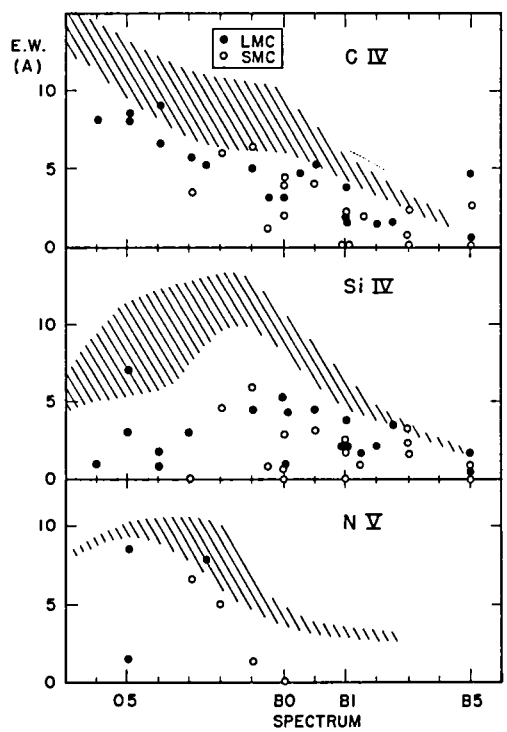

Fig. 4. UV resonance line strengths compared with galactic (hatched areas), from Hutchings (1982).

1982, 1983, Bruhweiler et al. 1982). Figures 4,5 illustrate the differences. Briefly, the resonance lines are weaker and the the terminal velocities of the winds lower in the Clouds than the galaxy, with the SMC being the extreme, as usual. Once again, the effect may be attributed to the heavy element abundance, as it is principally responsible for the radiative opacity which is a major effect in driving hot stellar winds. The exact way in which the winds differ is not understood - for example, the velocity gradients in the visible spectra are larger in the Clouds than the galaxy (Hutchings 1980a) - but the mass-loss mechanisms are not well modelled in the galaxy either. Bruhweiler et al. (1982) suggest that the mass loss rates may be similar in the SMC and galaxy, if the lower C and S abundances somehow balance out the lower line velocities and strengths. However, this actually assumes a greater efficiency if these lines drive the winds, and it seems more likely that all elements are similarly weakly driven. Looking at the W-R stars, Smith and Willis (1983) find that the velocities in these dense winds are similar to galactic ones, and that the abundances are similar to galactic, so that in their (more advanced ?) evolutionary state, the differences may diminish. However, they find that the He II lines are stronger in Cloud WN stars, and the extent of the envelopes is lower.

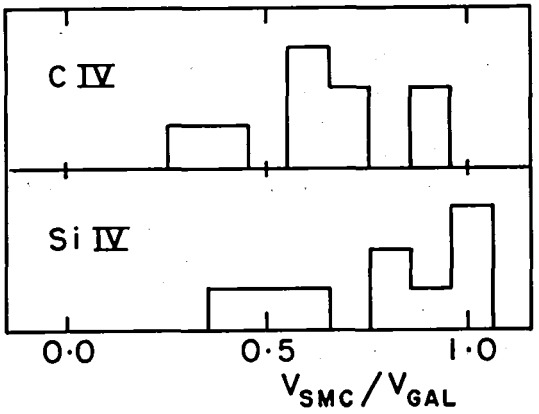

Fig. 5. Resonance line (minimum) velocity ratios SMC/galaxy, from Bruhweiler et al. (1982).

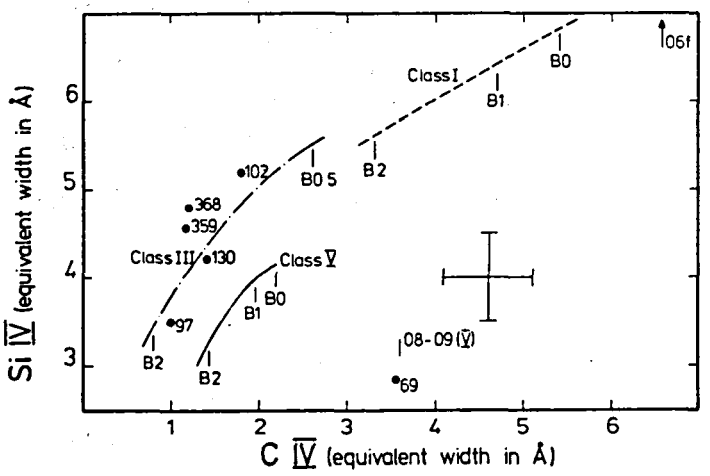

Fig. 6. LMC UV line strengths for giants compared with galactic stars (lines), from Nandy et al. (1983).

Looking at lower luminosity stars, Nandy et al. (1983) find that the resonance line strengths in giants are the same as their galactic counterparts, as are the flux distributions (fig. 6). Thus it may be that only at the highest luminosities do the differences become very apparent. Nevertheless, it is likely that the amount of mass lost from hot stars in the Clouds is considerably less than for their galactic counterparts, and that the evolution of massive stars is significantly different as a result. A further clue may reside in M33 and M31, whose populations of giant H II regions and W-R stars are also different, and suggest a general evolutionary sequence for galaxies which affects the most massive stars. We return to further aspects of this in the X-ray source section. For the future, we will need to study

massive stars in the UV in other galaxies with ST, and also to develop stellar wind models which explicitly embody the initial heavy metal abundance and synthesis in the stars.

There are several individual stars which have been studied in detail with IUE, at both low and high dispersion, and the results have generally been used in conjunction with ground based data in discussing the stars. Stahl et al. (1983), for example derive very high mass loss rates for a group of stars claimed to be like S Dor. Whether these are like galactic counterparts or not is not certain to me at present, mainly because local extinction has prevented the study of such objects in the UV. Kafatos et al. (1983) have studied two peculiar (symbiotic?) stars with IUE. Their results are significant in that, once again, the absolute luminosity of the hot star can be derived, with resulting implications for its mass and evolutionary history. Other extreme objects which have been studied are HD 38489 (Shore and Sanduleak 1983) and HD 34664 (Bensammar et al. 1983). Here, our sample needs to be extended both to other galaxies (the Hubble-Sandage variables) as well as our own galaxy in future UV work.

A final object of exceptional interest has been the apparently super-luminous (supermassive?) star R136a at the centre of 30 Dor (Feitzinger, Hanuschik, Schmidt-Kaler 1983, Moffat and Seggewiss 1983, Savage et al. 1983). The question in essence is whether the flux, (which IUE data show to be hot: > 50000 K) originates in a single star or a compact group of very early O stars. IUE data, in the above references, have been vital in deriving the flux, temperature and mass-loss characteristics of the star(s). The whole question now appears to rely on high resolution spatial imaging, yet to be done definitively (see full discussion in IAU Symp. 108). Whatever the object is, we note that Massey and Hutchings (1983) find similar objects powering similar giant H II regions in the similar galaxy M33. M31 does not appear to contain such objects, again suggesting a global sequence in galaxies.

X-RAY SOURCES

X-ray binaries in the Clouds are not numerous, but scale roughly with the galaxy mass (see Helfand 1984, Hutchings 1984). Nevertheless, they have several special and probably important properties. The cloud binary sources are much more luminous than their galactic counterparts. They also contain the two most rapid X-ray pulsars, strong evidence for luminous disks in massive systems, and two probable black holes in binary systems, in a volume of space which in the galaxy contains less than one. Once again, the single parameter which may be responsible is the abundance, this time affecting the opacity to X-rays. A low opacity to X-rays means that a higher accretion rate is possible on to a compact star, leading to higher luminosity and more rapid spinup of pulsars, as well as the formation of a stable and luminous accretion disk. The possible presence of massive stellar remnants suggests, as in the discussions above, that a history of lower mass-loss together with a collapse which is less opaque to radiation may allow the formation of more massive remnants than in the galaxy, where neutron stars (and supernovae?) are the norm.

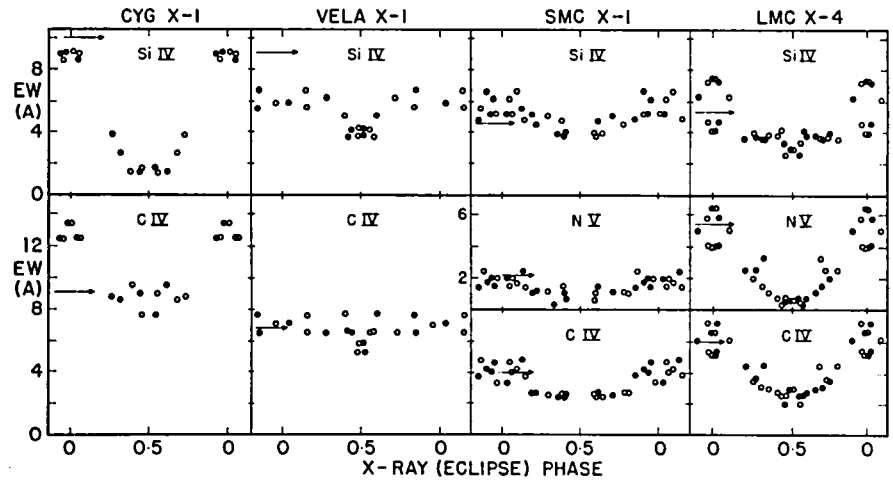

Fig. 7. Phase dependence of UV resonance lines in X-ray binaries in MCs and galaxy. Arrows indicate normal galactic values.

IUE investigations have been made on SMC X-1, LMC X-4, LMC X-1 and A0538-66. In the former two cases (van der Klis et al. 1982), the UV light curves were derived, which enabled modelling of the tidally distorted primary and the light from the disk. In LMC X-4 the data are consistent with precession of a disk on the 30-day period seen in the X-ray intensity. These studies also revealed the ionisation of the stellar winds by the X-rays by the phase dependence of the resonance lines (see also Hammerschlag-Hensberge, Kallman, Howarth 1984). The results are qualitatively similar to the galactic systems (fig. 7), but we need higher signal-to-noise data from future observations to make the important study of the different wind structures and UV photometric behaviour that these systems allow.

The unique variable system A0538-66 has been a fruitful object of IUE study. This system undergoes large optical changes in its 16-day cycle, as well as extended high and low states. Studies by Charles et al. (1983), and Howarth et al. (1983), have shown that the UV flux does not undergo these large changes, so that the effective temperature is lower in high optical states (fig. 8). While we do not get understand the system it is clear that the UV data form a vital part of our study of it. The unique high luminosity in X-rays, high mass-flow and associated optical and UV emitting volume make the understanding of the evolutionary state of this system of great interest. Once again, we look for LMC conditions that may contribute to its unique behaviour.

HALOS

The discovery of the galactic halo by IUE (Savage and de Boer 1979) is now well established by means of UV interstellar absorptions (e.g.C II, Mg II) which are much more sensitive probes than any visible lines. High dispersion studies of MC stars with IUE have also suggested halos associated with these galaxies (de Boer and Savage 1980), but the evidence is less secure. This is because it is difficult to get good data, and because the absorption lines have to be separated from galactic halo and local absorptions around the target stars (e.g. Feitzinger and Schmidt-Kaler 1982). de Boer (1984) gives a

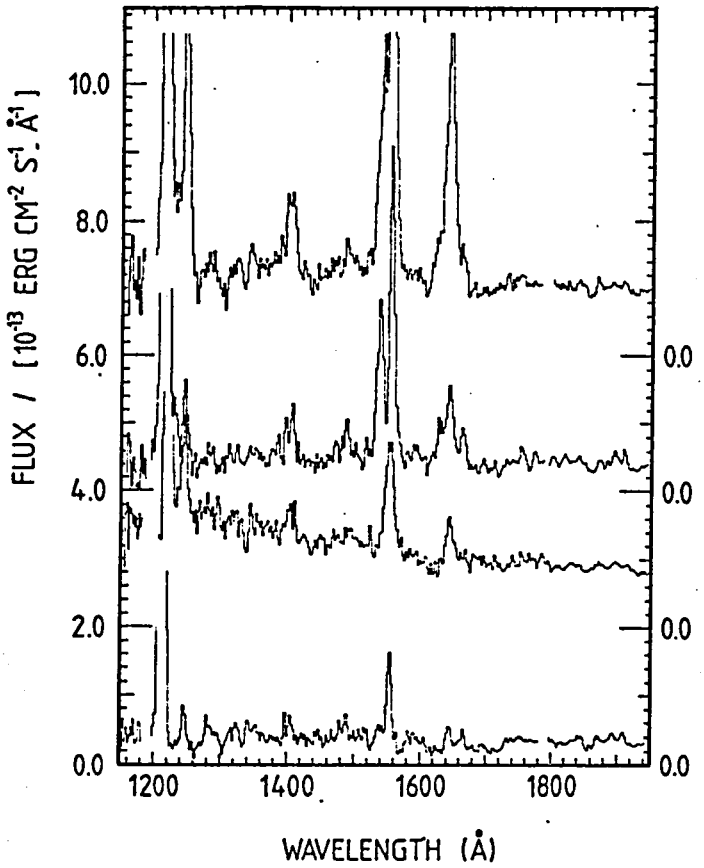

Fig. 8. A0538-66 in various activity states. Note profile, flux, and temperature changes. From Howarth et al. (1983).

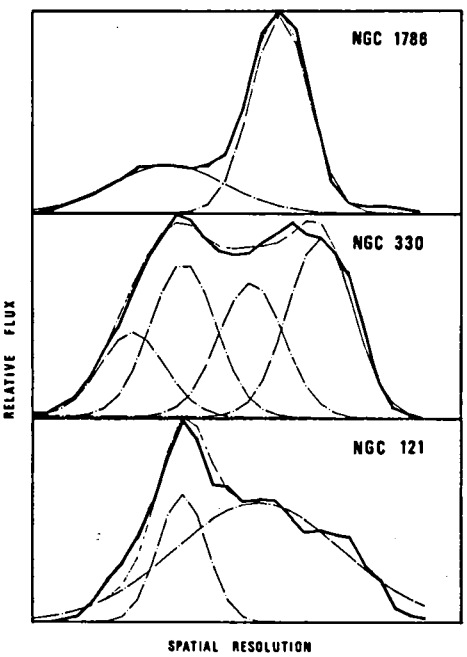

Fig. 10. Cross-sections of IUE spectra of MC clusters, deconvolved into principal components. From Cassatella and Geyer (1984).

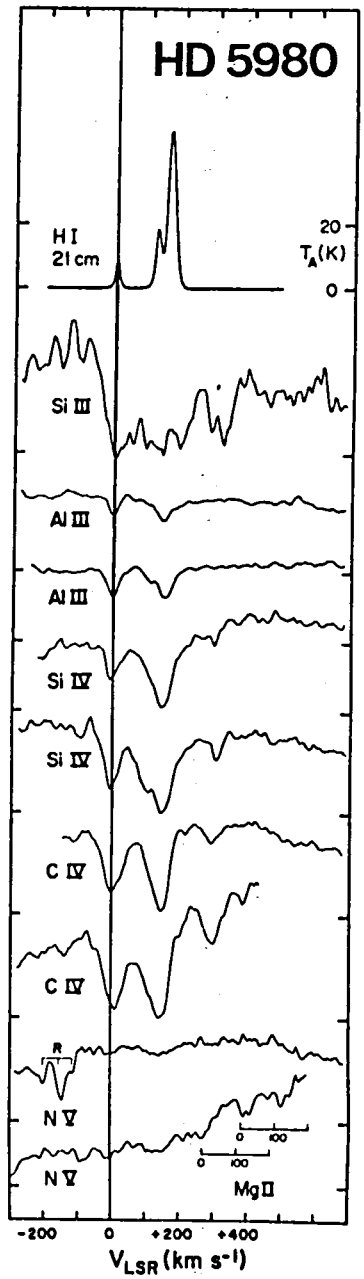

Fig. 9. Interstellar lines in HD 5980, from Fitzpatrick and Savage (1983). Zero velocity component is galactic.

review of the subject, and Fitzpatrick and Savage (1983) give perhaps the best data to date (fig. 9). Table 2 shows that the sharp absorptions in the MC stars are generally larger than for local galactic stars, suggesting that a halo is responsible for the excess. It is of importance to establish the presence or otherwise of these halos since their formation and heating is directly linked to the present stellar wind and supernova activity in the Clouds. There is also the interesting question of whether the halo as a whole rotates more slowly than the stars, as some evidence suggests. Once again, the proper study of the question requires the resolution and signal-to-noise of the Space Telescope HRS.

Table Equivalent Widths for Interstellar CIV Lines in MC Stars and Comparable Milky Way Stars

MC star		Sp. Type	V(star)	V(CIV)	W(1550)	Ref	MW star	Sp. Type	W(1550)	Ref
Sk-67 18	--	O6-7+WN5	272	240:	200:	dBS	HD153919	O6f	90	BKM
Sk-67 5	HD268605	O9.7Ib	294	250:	>150:	dBS	HD213087	B0.5Ib	65	BDHR
Sk-67 104	HD 36402	WC5+OB	315	270	200	dBN	HD113904	WC6+09BOI	80:	BKM
Sk-69 246	HD 38282	WN6	245:	210	230	dBS	HD192163	WN6	320	SWW,1
Sk-71 45	HD269676	O4-5III	229	220	270	GWMN	HD 46223	O4Vf	100	BDHR
Sk-69 243	HD 38268	R 136	245:	215	600	dBS	HD 37022	O6+B0.5V	260	FS,2
Sk 108	R31	O6.5+WN3	129	150	300	dBS	HD 93403	O6f+O7.5	150	BKM
Sk 80	---	O7Iaf+	---	150	280	dBS	HD 57060	O7f	30	BKM
Sk 78	HD 5980	OB?+WN3	---	140	410	dBS	HD190918	WN5+O9.5III	470	BKM,1
Sk 159	---	BOIa	---	170	60	P9	HD152667	BOIa	75	BKM

Table 2. From Koornneef (1984). Note large W values of MC stars, possibly due to halo absorption.

CLUSTERS

As a final section, we look at the efforts to study Cloud globular clusters with IUE (de Boer, 1981; Cacciari et al., 1982; Cassatella and Geyer 1982). These studies have revealed the presence and temperature of hot stars, allowing estimates to be made of their numbers. The absence of extinction suggests that the original cluster gas has either been used up or blown away. Luminosity functions derived for clusters from IUE data have yielded ages in the range 7×10^6 to 8×10^7 years. In some clusters (fig. 10), the spectra of individual stars can be deconvolved, and temperatures derived, which range in general from 12000-30000 K. Bohm-Vitense and Hodge (1984) find LMC type extinction in clusters, and also note the absence of mass loss in LMC stars whose galactic counterparts do show mass loss. These are all important UV studies which will yield significant results on cluster evolution and MC star formation history, and clearly need much future work.

In conclusion, I hope this very superficial report will encourage the pursuit of MC research in the UV. The Clouds appear to form the early part of a sequence in galaxy evolution, which can be traced through the principal local group members. The UV contains much of the vital information in learning about this sequence, and the history of the Clouds themselves.

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